
Antiproton Stacking and Cooling

Dave McGinnis
Director's Review
July 1, 2003

Outline

- Parameter Goals
- Strategy
- Antiproton Stacking Process
- Projects
- Project Strategy
- Key Parameters
- Cost and Schedule

Parameter Goals

■ Goals

- Average Stacking Rate 40×10^{10} pbars/hour
- Stack at this rate for at least 15 hours
- Final Stack Parameters
 - Size = 625×10^{10} pbars
 - Transverse emittance $< 15\pi$ -mm-mrad (95% normalized)
 - Longitudinal emittance < 50 eV-Sec

■ Inputs

- Collect 280×10^6 antiprotons from the target every 2 seconds
 - Transverse emittance = 35π -mm-mrad (95% un-normalized)
 - Momentum Spread = 4%
 - Bunch lengths < 1.5 nS

Strategy

- Present Run II Operations
 - Accumulator Core is the final repository for antiprotons
 - Bandwidth
 - Momentum aperture
 - Stacktail gain slope
 - 1/N effect in stochastic cooling limits stack size to $\sim 300 \times 10^{10}$ pbars
- Run II Upgrades
 - The Recycler is the final repository for antiprotons
 - Electron cooling in the Recycler greatly reduces the 1/N effect
 - Larger average/peak stacking rate ratio
 - Larger stacks $\sim 600 \times 10^{10}$
 - Accumulator Stacktail is optimized to handle larger flux by larger bandwidth and smaller gain slope
 - Greatly reduced Accumulator core size is also a result of larger bandwidth and smaller gain slope
 - Reduced Accumulator core size and high stacking rates require frequent and rapid transfers between the Accumulator and the Recycler

Antiproton Stacking Process

- Debuncher Bunch Rotation

- Exchange

- Large Momentum spread of 4% (360 MeV)
 - Short bunches < 1.5 nS (95%)

- For

- Small momentum spread of 0.4% (36 MeV)
 - Coasting beam

- Debuncher Cooling

- System Configuration

- Liquid Helium front end ($T_{\text{eff}}=30\text{K}$)
 - Bandwidth = 4-8 GHz Subdivided into 4 bands
 - Available kicker power
 - 2400 Watts/ plane (transverse)
 - 4800 Watts (momentum)

- Cooling Rate Specs.

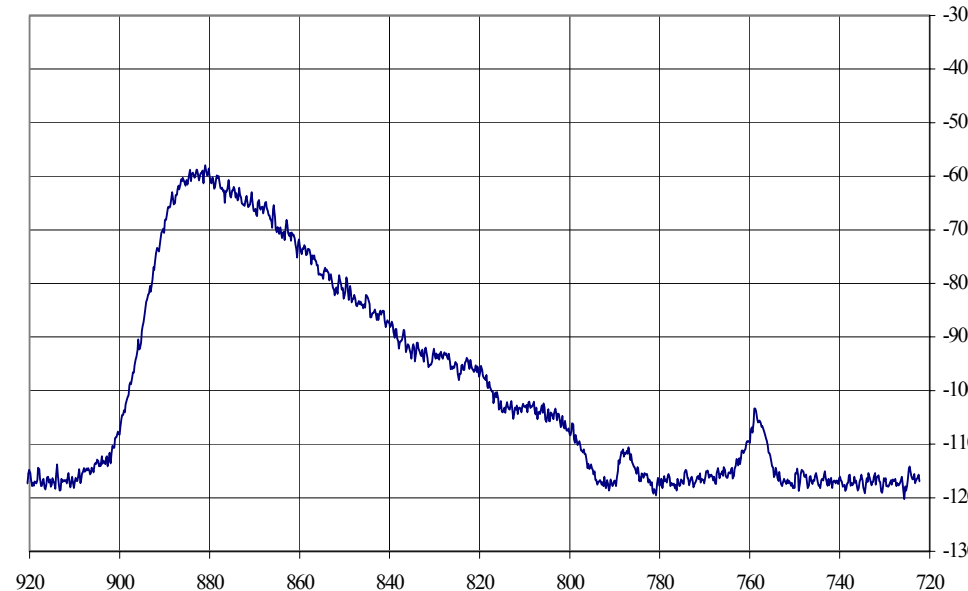
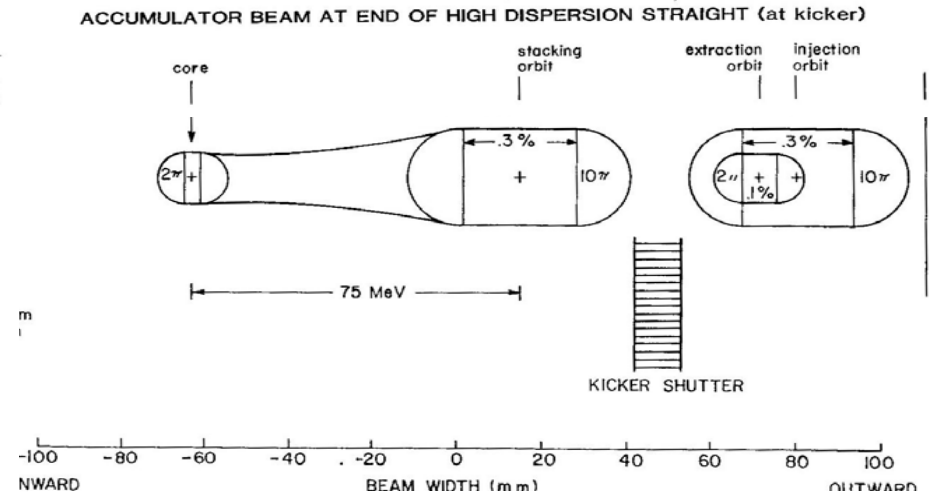
- Momentum: 36 MeV to 6 MeV in 1.9 Seconds
 - Transverse: 35π -mm-mrad to 5π -mm-mrad (95% un-normalized) in 1.9 seconds

Antiproton Stacking Process

■ Accumulator Stacktail Cooling

➤ Process

- Beam is injected onto the Injection Orbit
- Beam is
 - Bunched with RF
 - Moved with RF to the Stacking Orbit
 - Debunched on Stacking orbit
- Stacktail pushes and compresses beam to the Core orbit
- Core Momentum system gathers beam from the Stacktail
- Accumulator Transverse Core Cooling system cools the beam transversely in the Stacktail and Core



Antiproton Stacking Process

- Accumulator Stacktail Cooling
 - Specifications
 - Injection pulse width: 6 MeV
 - Stacktail:
 - Bandwidth = 2-6 GHz
 - Width = 42 MeV
 - Gain slope = 8 MeV (can handle 90×10^{10} pbars/hr)
 - Power = 550W into 6400Ω
 - Core momentum
 - Bandwidth = 4-8 GHz
 - Aperture = 9.6 MeV
 - Gain slope = 5 MeV (can handle 90×10^{10} pbars/hr)
 - Stacksize = 34×10^{10} pbars
 - Extraction
 - Longitudinal emittance: 10eV-sec
 - Transverse emittance 1.0π -mm-mrad
 - Stacking interval: 30 minutes
 - Transfer size: 22.5×10^{10} pbars

Antiproton Stacking Process

■ Recycler Electron Cooling

- Every $\frac{1}{2}$ hour an injected batch of 22×10^{10} pbars in 10 eV-Sec and 1.0π -mm-mrad phase space is injected into the Recycler
 - Transfers between the Accumulator and the Recycler
 - Are done on "event"
 - » ~instantaneously
 - » No more mini-shot setup
 - A 50% dilution is assumed to occur on each transfer
 - » 15 eV-Sec and 1.5π -mm-mrad phase space
 - Transverse stochastic pre-cooling of the injected batch
 - To bring the transverse emittance of the injected batch within the reach of the electron cooling
 - The injected batch is kept separate from the main "core" by barrier buckets
 - Transverse stochastic cooling systems are "gain gated"
 - » Low density injected batch - fast stochastic cooling
 - » High density core - slow stochastic cooling

Antiproton Stacking Process

■ Recycler Electron Cooling

- Every $\frac{1}{2}$ hour, the previous injected batch is merged into the core with barrier bucket manipulations to make room for the new injected batch
- The Recycler Core
 - Is cooled mainly with electron cooling in all 3 planes
 - Weak transverse stochastic cooling for high amplitude particles
 - Intra-beam scattering (IBS) is "shut-off"
 - Recycler
 - » operates below transition
 - » has low dispersion
 - » has smooth lattice functions
 - The Core is squeezed with barrier buckets so that it occupies only 20% of the machine circumference
 - The transverse emittance is cooled to less than 0.3π -mm-mrad (95% un-normalized) so that the beam temperature in all 3 planes is equal

Antiproton Stacking and Cooling Projects

- Accumulator Stacktail Upgrade
 - Project Leader: Paul Derwent
 - Major Objectives: Upgrade the Stacktail system to handle 90×10^{10} pbars/hour
 - Increase bandwidth of the system to 2-6 GHz
 - Reduce gain slope ~ 10 MeV
- Electron Cooling in the Recycler
 - Project Leader: Sergei Nagaitsev
 - Major Objectives: Install a 4.3 MV Pelletron in the Recycler
 - 500 mA of electron current
 - 20 meters of cooling section
- Rapid Antiproton transfers from the Accumulator to the Recycler
 - Project Leader: Elvin Harms
 - Major Objectives: Transfer Accumulator core to the Recycler
 - in less than 1 minute every 30 minutes
 - $< 50\%$ emittance dilution
 - 95% transfer efficiency

Antiproton Stacking and Cooling Projects

WBS	Subproject	In Charge	Finish Date	M&S Est	M&S Cont
1.3.3	Pbar Stacking and Cooling	Dave McGinnis	11/17/05	\$2,254,000.00	46%
1.3.3.1	Stacking and Cooling Integration	Dave McGinnis	11/4/05	\$0.00	
1.3.3.2	Debuncher Cooling	Paul Derwent	6/2/03	\$0.00	
1.3.3.3	Stacktail Cooling	Paul Derwent	11/17/05	\$1,171,000.00	40%
1.3.3.3.1	Momentum	Paul Derwent	11/17/05	\$1,004,000.00	40%
1.3.3.3.2	Betatron	Paul Derwent	11/17/05	\$167,000.00	40%
1.3.3.4	Recycler Stacking and Cooling	Sergei Nagaitsev	4/8/05	\$0.00	
1.3.3.5	Electron Cooling	Sergei Nagaitsev	1/25/05	\$566,000.00	44%
1.3.3.5.1	Commission Full Beamline	Sergei Nagaitsev	3/19/04	\$55,000.00	45%
1.3.3.5.2	Design and procure components	Jerry Leibfritz/Sergei Na	1/30/04	\$373,000.00	42%
1.3.3.5.3	Disassemble Wideband Facility	Jerry Leibfritz/Sergei Na	6/1/04	\$22,000.00	58%
1.3.3.5.4	Transport Components to MI-31	Jerry Leibfritz	7/27/04	\$24,000.00	60%
1.3.3.5.5	Install Pelletron at MI-31	Jerry Leibfritz/Sergei Na	8/10/04	\$37,000.00	60%
1.3.3.5.6	Commission Pelletron	Sergei Nagaitsev	10/19/04	\$0.00	
1.3.3.5.7	Install E-Cool Transferline	Jerry Leibfritz	8/27/04	\$23,000.00	40%
1.3.3.5.8	Modifications to MI/RR	Jerry Leibfritz	9/18/03	\$15,000.00	40%
1.3.3.5.9	Install Cooling Section in RR	Jerry Leibfritz/Sergei Na	9/6/04	\$17,000.00	40%
1.3.3.5.10	Commission Cooling Section	Sergei Nagaitsev	9/23/04	\$0.00	
1.3.3.5.11	Commission Electron Cooling	Sergei Nagaitsev	1/25/05	\$0.00	
1.3.3.6	Rapid Transfers	E Harms	5/5/05	\$517,000.00	60%
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1.3.3.6.2	Beam Line Regulation	E Harms	2/13/04	\$12,000.00	40%
1.3.3.6.3	RT Software	E Harms	3/4/05	\$0.00	
1.3.3.6.4	Oscillation Feedback and Control	B Foster	1/9/04	\$0.00	
1.3.3.6.5	Diagnostics	E Harms	12/16/04	\$505,000.00	60%
1.3.3.6.6	Commission Fast Transfers	E Harms	5/5/05	\$0.00	

Accumulator Stacktail Upgrade Project Strategy

- Design margin for flux = 90×10^{10} pbars/hour

$$\Phi_o = \frac{|\eta| W^2 E_d}{f_o \beta_{pc} \ln\left(\frac{f_{\max}}{f_{\min}}\right)}$$

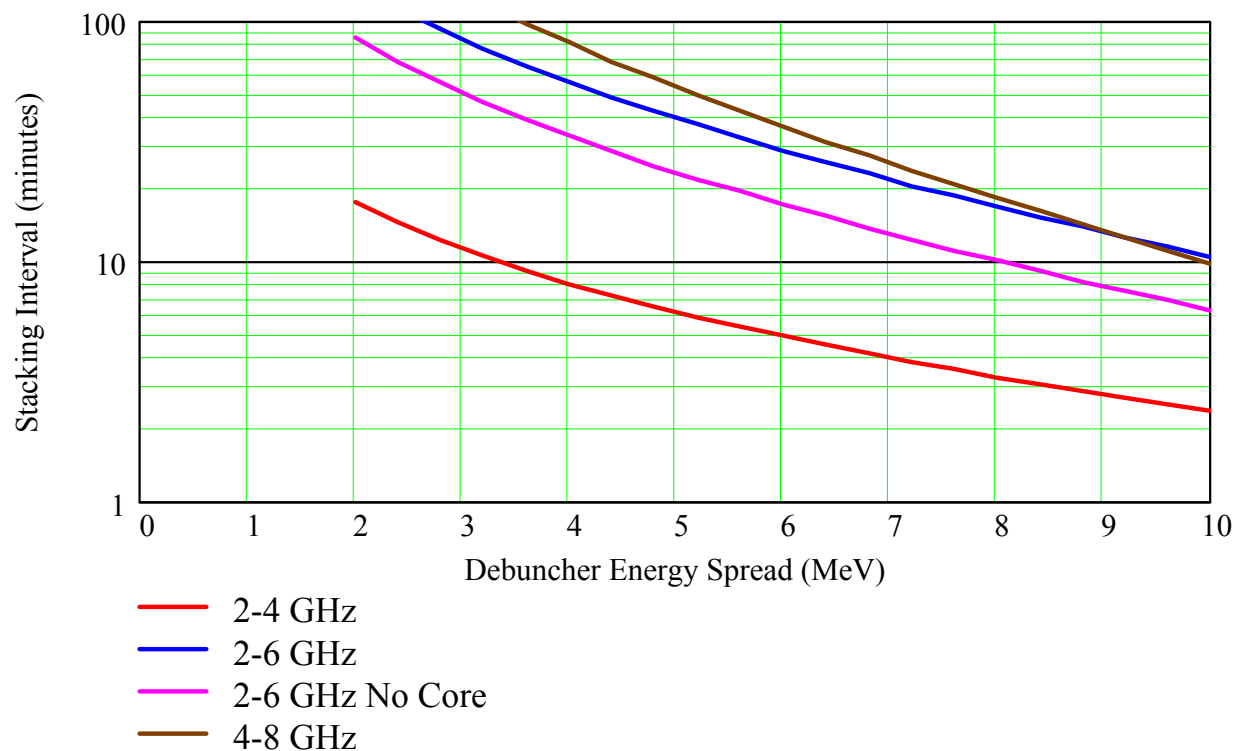
- The best way to increase flux is to increase the bandwidth
- Large E_d needs a large momentum aperture or results in a low final core density
- Energy Aperture and Stability
 - Would like energy aperture as big as possible to get a large core density
 - For system stability, operate at frequencies where Schottky bands do not overlap
 - Strategies
 - Reduce η
 - Increases β functions - decreases aperture
 - Increases intra-beam scattering heating
 - Reduce momentum aperture of cooling system
 - Core Momentum system with higher bandwidth
 - Energy aperture of core is limited by "bad" mixing between pickup and kicker at high frequencies

Accumulator Stacktail Upgrade Project Strategy

■ Core Density and Stacking Interval

- Particles to be transferred must be inside desired Recycler longitudinal emittance
- Desire long stacking interval
 - Small Debuncher energy spread ΔE_{bd}
 - Large energy aperture $\Delta E_s + \Delta E_c$
 - Small characteristic energy slope (E_d)

Stacktail Bandwidth	Core Bandwidth	E_{ds}	E_{dc}	$\Delta E_s + \Delta E_{bd}$	ΔE_c	Fraction Unstacked
(GHz)	(GHz)	(MeV)	(MeV)	(MeV)	(MeV)	(%)
2-4	4-8	20	5	77.4	9.6	50
2-6	4-8	8	5	48.4	9.6	66
2-6	2-6	8	8	45.2	12.8	55
4-8	4-8	5	5	33.9	9.6	72



Recycler Electron Cooling Project Strategy

- Decide on whether to do longitudinal cooling and/or betatron cooling
 - Longitudinal cooling rate independent of β function
 - Important for the Recycler
 - Transverse cooling rate proportional to $\beta^{1/2}$
 - Not as important for the Recycler
- Design for minimum angular spread in electron beam
 - Cooling section solenoid field quality
 - Aberrations in the beamline
 - Stability of the antiproton orbit
 - Stability of the electron optics
 - Emittance and space charge
 - Stray magnetic fields
- Decide on reasonable emittance range for optimum cooling

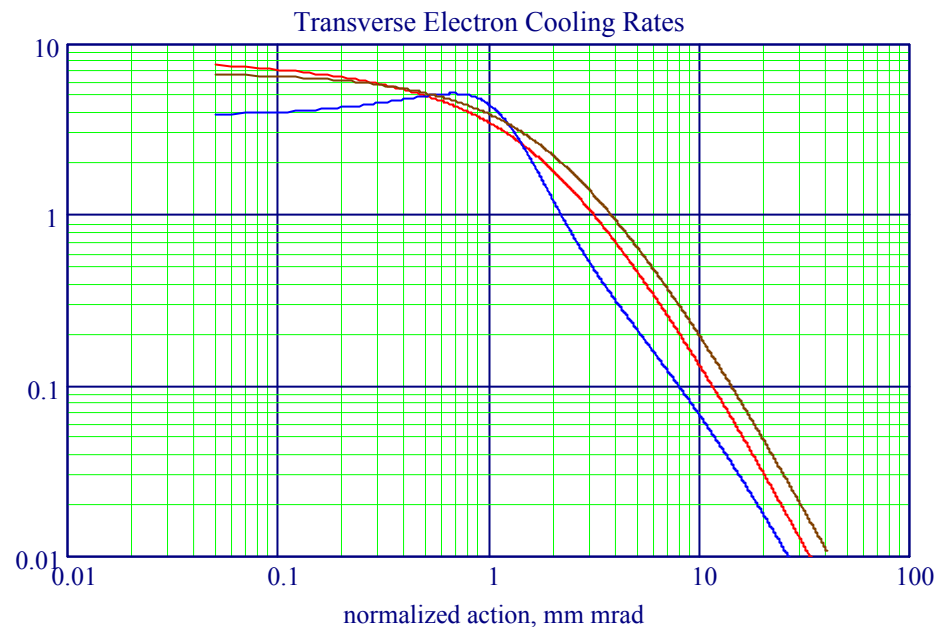
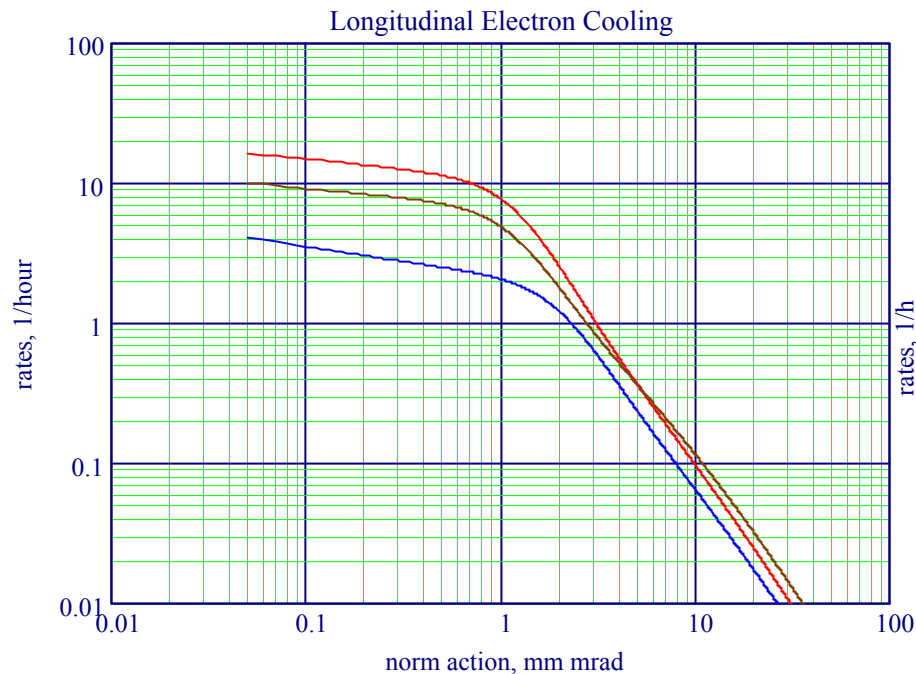
$$\sqrt{\frac{\epsilon_{95\%}}{6\beta}} \approx \Delta\theta_{\text{electron spread}}$$

$$r^2 = \epsilon_{95\%}\beta$$

- Design electron beam size

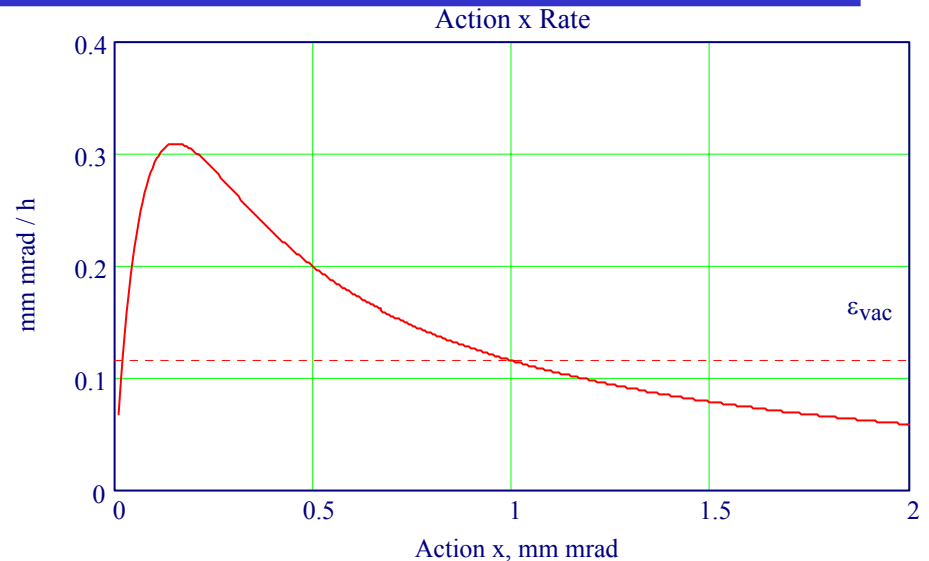
Recycler Electron Cooling Project Strategy

- Emphasis on longitudinal cooling
- Electron Beam Current = 500 mA
- Angular spread of electron beam = 0.22 mrad
- Design cooling for transverse emittance of 3π -mm-mrad (normalized) with Electron beam size = 3 mm with $\beta=22\text{m}$
- Longitudinal Cooling time needed = 25 minutes

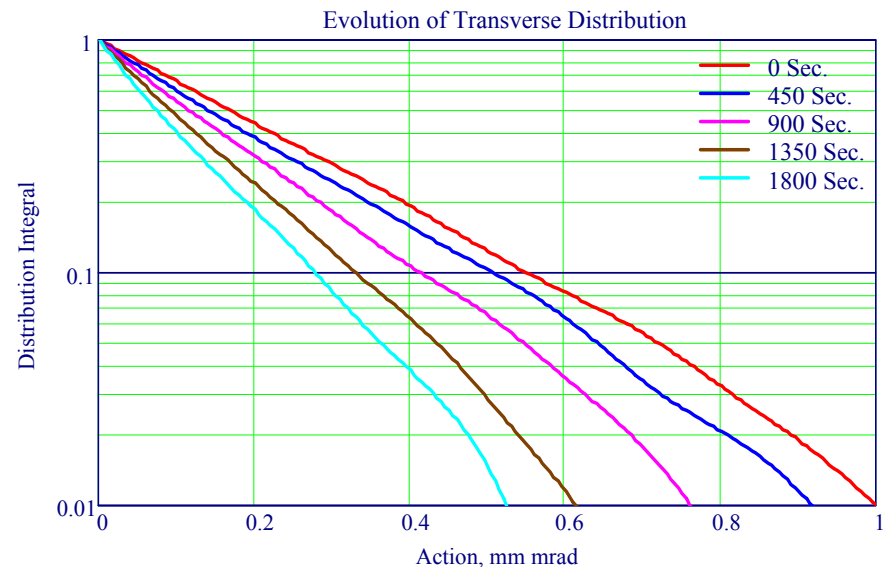


Recycler Stochastic Pre-cooling and Vacuum

- Needed to transversely pre-cool 22×10^{10} pbars injected from the Accumulator for $\frac{1}{2}$ hour to bring the transverse emittance within reach of the electron cooling



- Evolution of the injected batch with 22×10^{10} pbars using a Q=1 2-4 GHz Transverse Stochastic Cooling system, 0.7π -mm-mrad/hr vacuum growth rate



Rapid Transfers Project Strategy

- Transfers are done on event
 - Halt to stacking
 - Accumulator RF Extraction
 - Transfer to the Recycler
 - Recycler Barrier Bucket manipulation
 - Return to stacking
- P1, P2, and AP1 power supplies ramp on every event
 - No more bi-modal operation of AP1
- Fast Feedback
 - Random oscillations are corrected by injection dampers in the Main Injector and Recycler
 - 1 kV in ~80 turns will damp 2π -mm-mrad (95% normalized) oscillation
 - 8 GeV transfer line magnet power supplies regulation specification to 2π -mm-mrad
- Slow Feed-Forward
 - Transfer line reference orbit
 - Transfer line BPM system
 - Injection oscillations
 - Turn-by-turn info provided by damper systems.

Key Parameters

Parameter	Value	Unit
Average Stacking rate	40	$\times 10^{10}$ per hour
Peak Stacking rate	45	$\times 10^{10}$ per hour
Number of particles injected into the Debuncher	280	$\times 10^6$
Debuncher transverse aperture	35	π -mm-mrad
Antiproton production cycle time	2	Secs
Maximum bunch length on target	1.5	nSecs.
Debuncher momentum aperture	4	%
Debuncher momentum cooling aperture	0.4	%
Debuncher final transverse emittance	5	π -mm-mrad
Debuncher final momentum spread	6	MeV
Debuncher transverse cooling common mode rejection	1.5	mm
Debuncher transverse cooling phase imbalance	3	degrees
Debuncher transverse cooling delay imbalance	1.4	pS
Debuncher momentum notch filter delay tolerance	1	pS
Debuncher momentum cooling notch filter dispersion	2.5	degrees
Debuncher to Accumulator transfer efficiency	95	%
Accumulator Stacktail Momentum bandwidth	2-6	GHz
Accumulator Core Momentum bandwidth	4-8	GHz
Accumulator Stacktail Momentum energy slope	8	MeV
Accumulator Stacktail Power	625	Watts
Accumulator Stacktail 2-6 GHz kicker impedance	6400	Ω
Accumulator Core Momentum energy slope	5	Mev
Accumulator Core Momentum cooling aperture	9.6	MeV
Accumulator Momentum cooling aperture	58	MeV

Key Parameters

Parameter	Value	Unit
Accumulator Momentum cooling aperture	58	MeV
Accumulator to Recycler transfer longitudinal emittance	10	eV-Sec
Accumulator to Recycler transfer interval	30	minutes
Number of particles extracted from the Accumulator per transfer	24	$\times 10^{10}$
Accumulator to Recycler transfer time	1	minutes
Accumulator to Recycler transfer efficiency	95	%
Accumulator core transverse emittance	1	π -mm-mrad
Recycler transverse emittance injection dilution	50	%
Recycler longitudinal emittance injection dilution	50	%
Recycler transverse Stochastic Cooling Bandwidth	>1	GHz
Recycler Transverse Stochastic cooling Center Frequency	3	GHz
Maximum Recycler Transverse emittance Growth Rate	0.7	π -mm-mrad/hr
Peak Stack in Recycler	620	$\times 10^{10}$
Transverse emittance of antiprotons extracted from Recycler	1	π -mm-mrad
Total Longitudinal emittance of antiprotons extracted from Recycler	50	eV-Sec
Number of bunches extracted from the Recycler	36	
Minimum longitudinal cooling rate of Electron Cooling	55	eV-Sec/hour
Minimum Electron Cooling Current	250	mA
Electron Beam alignment tolerance	0.1	mrad
Transverse electron cooling rate per 100 mA	0.12	π -mm-mrad
Maximum transverse emittance for electron cooling	1.5	π -mm-mrad

Key Parameter Comparison

Parameter	Value FY06	Value FY04	Value Now	Unit
Average Stacking rate	40	12	8.5	$\times 10^{10}$ per hour
Peak Stacking rate	45	18	13	$\times 10^{10}$ per hour
Beam on Target	8	5	4.7	$\times 10^{12}$
Number of particles injected into the Debuncher	280	100	90	$\times 10^6$
Debuncher transverse aperture	35	15	15	π -mm-mrad
Antiproton production cycle time	2	1.7	2.2	Secs
Maximum bunch length on target	1.5	1.3	1.3	nSecs.
Debuncher momentum aperture	4	3.7	3.7	%
Debuncher momentum cooling aperture	0.4	0.4	0.4	%
Debuncher final transverse emittance	5	5	5	π -mm-mrad
Debuncher final momentum spread	6	5	9	MeV
Debuncher transverse cooling common mode rejection	1.5	1	<1	mm
Debuncher transverse cooling phase imbalance	3	20	30	degrees
Debuncher transverse cooling delay imbalance	1.4	10	14	pS
Debuncher momentum notch filter delay tolerance	1	1	2-3	pS
Debuncher momentum cooling notch filter dispersion	8	10	20	degrees
Debuncher to Accumulator transfer efficiency	95	95	95	%
Accumulator Stacktail Momentum bandwidth	2-6	1.7-3.7	1.7-3.7	GHz

Key Parameter Comparison

Parameter	Value FY06	Value FY04	Value Now	Unit
Accumulator Core Momentum bandwidth	4-8	4-7	2-4	GHz
Accumulator Stacktail Momentum energy slope	8	11	11	MeV
Accumulator Stacktail Power	625	280	250	Watts
Accumulator Stacktail 2-6 GHz kicker impedance	6400	6400	6400	Ω
Accumulator Core Momentum energy slope	5	6	11	Mev
Accumulator Core Momentum cooling aperture	9.6	12	20	MeV
Accumulator Momentum cooling aperture	58	72	80	MeV
Accumulator to Recycler transfer longitudinal emittance	10	15	15	eV-Sec
Accumulator to Recycler transfer interval	30	180	180	minutes
Number of particles extracted from the Accumulator per transfer	24	24	25	$\times 10^{10}$
Accumulator to Recycler transfer time	1	15	60	minutes
Accumulator to Recycler transfer efficiency	95	90	70	%
Accumulator core transverse emittance	1	1	1	π -mm-mrad
Recycler transverse emittance injection dilution	50	50	>100	%
Recycler longitudinal emittance injection dilution	50	50	>100	%
Peak Stack in Recycler	620	200	80	$\times 10^{10}$
Transverse emittance of antiprotons	1	1	-	π -mm-mrad
Total Longitudinal emittance of antiprotons	50	50	100	eV-Sec
Transverse stochastic cooling time @ 100e10	0.7	0.7	-	hours

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1.3.3.5	Electron Cooling	Sergei Nagaitsev	1/25/05	\$566,000.00	44%
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1.3.3.5.8	Modifications to MI/RR	Jerry Leibfritz	9/18/03	\$15,000.00	40%
1.3.3.5.9	Install Cooling Section in RR	Jerry Leibfritz/Sergei Na	9/6/04	\$17,000.00	40%
1.3.3.5.10	Commission Cooling Section	Sergei Nagaitsev	9/23/04	\$0.00	
1.3.3.5.11	Commission Electron Cooling	Sergei Nagaitsev	1/25/05	\$0.00	
1.3.3.6	Rapid Transfers	E Harms	5/5/05	\$517,000.00	60%
1.3.3.6.1	Document Fast Transfer scheme	E Harms	4/21/03	\$0.00	
1.3.3.6.2	Beam Line Regulation	E Harms	2/13/04	\$12,000.00	40%
1.3.3.6.3	RT Software	E Harms	3/4/05	\$0.00	
1.3.3.6.4	Oscillation Feedback and Control	B Foster	1/9/04	\$0.00	
1.3.3.6.5	Diagnostics	E Harms	12/16/04	\$505,000.00	60%
1.3.3.6.6	Commission Fast Transfers	E Harms	5/5/05	\$0.00	

Antiproton Stacking and Cooling Milestones

WBS	Subproject/Milestone	MS Class	MS Date
1.3.3	Pbar Stacking and Cooling		
1.3.3.3	Stacktail Cooling		
1.3.3.3.1	Momentum		
1.3.3.3.1.1.5	Review System Design: stacktail momentum (Milestone)	C	1/5/04
1.3.3.3.1.2.4	Stacktail Reconfigured (option) (Milestone)	C	8/10/04
1.3.3.3.1.9	Acc Momentum Operational (Milestone)	A	11/17/05
1.3.3.3.2	Betatron		
1.3.3.3.2.1.2	Review System Design: stacktail betatron (Milestone)	C	11/28/03
1.3.3.3.2.8	Acc Betatron Operational (Milestone)	A	11/17/05
1.3.3.4	Recycler Stacking and Cooling		
1.3.3.4.2	Commissioning Parameters Defined (Milestone)	C	5/30/03
1.3.3.4.4	Commissioning Plan Evaluation (Milestone)	B	11/14/03
1.3.3.4.5	RR Commissioned for Electron Cooling (Milestone)	A	7/2/04
1.3.3.5	Electron Cooling		
1.3.3.5.1	Commission Full Beamline		
1.3.3.5.1.11	Demonstrate beam properties at Wide Band Lab (Milestone)	B	3/19/04
1.3.3.5.2	Design and procure components		
1.3.3.5.2.1	Pelletron extension parts received (Milestone)	C	1/1/04
1.3.3.5.6	Commission Pelletron		
1.3.3.5.6.1	Pelletron Installed at MI-31 (Milestone)	C	8/11/04
1.3.3.5.12	Electron Cooling Operational (Milestone)	A	1/25/05
1.3.3.6	Rapid Transfers		
1.3.3.6.7	Rapid Transfers Operational (Milestone)	A	5/5/05
1.3.6.2	Project Milestones		
1.3.6.2.2	Review: RR and Electron Cooling Commissioning Plan (Milestone)	A	12/16/03
1.3.6.2.3	Review: Phase 2-4 Transition Plan (Milestone)	A	4/16/04

Drivers

■ Cost

- Accumulator Stacktail Upgrade
 - Travelling Wave Tubes
- Electron Cooling
 - 5 MV Pelletron (already purchased)
 - MI31 Civil construction (already underway)
 - Transfer line components
- Rapid Transfers
 - Transfer lines 53 MHz BPM Upgrade

■ Schedule

- Accumulator Stacktail Upgrade
 - Procurement of the Traveling Wave Tubes
- Electron cooling
 - Recycler commissioned for Electron Cooling
 - Electron beam properties measured at Wideband
 - Electron cooling installed at MI31